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CONTINUOUS ACOUSTIC SENSING WITH AN UNMANNED AERIAL VEHICLE SYSTEM FOR ANTI-SUBMARINE WARFARE IN A HIGH-THREAT AREA

by

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December 2015

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An unmanned aerial vehicle system called the "Aqua-Quad," an ultra-long-endurance hybrid design, developed by researchers in the NPS Department of Mechanical and Aerospace Engineering, is utilized in this thesis. The Aqua-Quad has the capability of landing on the ocean surface and deploying passive acoustic sensors at depth. We investigated the employment of the Aqua-Quad in a general environment, determined sea-state survivability, and verified, using a self-contained acoustic sensor, that the Aqua-Quad can be utilized in undersea warfare.

The experiments and data collected on the initial setup of the Aqua-Quad are compared against the Navy's current asset, passive sonobuoys. These comparisons will prove to be influential in the process of building, researching, and developing a new and improved sensor asset with unlimited potential to strive in multiple warfare areas.

This research benefits not only the Navy, through enhancement of offensive warfighting by testing the next generation of sonobuoys, but also the oceanographic community with fast sampling and detection.

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CONTINUOUS ACOUSTIC SENSING WITH AN UNMANNED AERIAL VEHICLE SYSTEM FOR ANTI-SUBMARINE WARFARE IN A HIGH-THREAT AREA

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LIST OF ACRONYMS AND ABBREVIATIONS

AOR	Area of Responsibility
ASW	Anti-Submarine Warfare
CNO	Chief of Naval Operations
COI	Contact of Interest
CPA	Closest Point of Approach
LFA	Low-Frequency Active
LTSA	Long-Term Spectral Averages
LOS	Line of Sight
Pd	Probability of Detection
RHIB	Rigid-Hull Inflatable Boat
SSP	Sound Speed Profile
TSP	Temperature, Salinity, and Pressure
UAV	Unmanned Aerial Vehicle
USW	Undersea Warfare
XBT	Expendable Bathythermograph

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First off, I would like to thank my supportive wife for her love and for letting me talk about the wonderful world of ASW and Aqua-Quads. Thanks also go to my beautiful daughter for giving me a reason to take a break to gather my thoughts and see her smile! Also, a huge thanks to all the friends and family that gave me recommendations and even just let me talk about the direction in which I wanted to go.

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I. INTRODUCTION

A. MOTIVATION

Increasing the capabilities of U.S. Navy assets in one of the critical mission areas of undersea warfare (USW) directly supports the Chief of Naval Operations' (CNO) "warfighting first" focus (Naval Surface and Mine Warfighting Development Center Public Affairs 2015). Vice Admiral Rowden has stated that "advancing combat capability and warfare competencies" shows not only where the surface force is headed, but indicates where the Navy as a whole is headed as well (Naval Surface and Mine Warfighting Development Center Public Affairs 2015). Utilizing advanced technology and research, the Navy is continually looking for ways to produce platforms that will help minimize manning (people on target who could possibly be killed) yet be able to conduct the mission fully in any area of responsibility (AOR). Unmanned systems are expected to play an increasing role in completing this goal. At the Naval Postgraduate School researchers have been developing a hybrid-UAV that may provide breakthrough technology, essentially providing the Navy with an aerial mobile sonobuoy, allowing it to "chase" an enemy contact of interest (COI) for extended periods.

B. HISTORY

Starting with the Cold War with Soviet/Russian submarines and moving forward to present day with Chinese submarines, the threat and capability of foreign nations' submarines has increased. The increase in the threat and in the capabilities of these submarines is an issue that the United States is continually working on to deter and if necessary defeat. The opposition is becoming even stealthier underwater, and they are moving the fight to shallow water, meaning there is a sudden demand for improved anti-submarine warfare (ASW) capability for the United States (Ultra Electronics Maritime Systems 2015).

Sonobuoy deployment has been a part of USW for quite some time. Whether they are deployed over the side on a surface ship or from an air asset, today's sonobuoys do the same job they have done since they were first deployed as an ASW asset. Passive

sonobuoys listen for acoustic noise and remain effective for target classification through signature analysis and medium frequency; active sonobuoys are effective for short-range target relocation and attack (Ultra Electronics Maritime Systems 2015). The greatest success, however, comes from the combination of a low-frequency active (LFA) sonobuoy and latest passive sonobuoy (Ultra Electronics Maritime Systems 2015).

Defense budgets are increasing in the area of sonobuoys due to the cutbacks from the wind down in Afghanistan and as U.S. military strategy transitions to an Asia-Pacific and more Navy-centric emphasis—more specifically, ASW is gaining "greater importance to counter both growing tensions in the South China Sea and a growing Chinese submarine threat (Shapiro 2013)." With this increase we propose to replace a system of 20–30 sonobuoys, priced $500–$2,500, and with a roughly 8-hour time on-station, with a smaller number of assets with comparable and possible better underwater sensing capability. Along with the similar sensing capability, we will add air mobility that allows them to track and follow COIs and a life span measured in months rather than hours.

II. THE AQUA-QUAD: FUTURE ASW SENSOR

Shipboard ASW sensors include hull-mounted sonar systems, active-passive towed sonar, airborne support of a SH-60, and lastly sonobuoys. Top brass along with ship commanders will both agree that the best choice to attack an enemy submarine is a U.S. submarine. Second choice is the airborne support and last is a ship. However, what if we could change that order, or let all three coexist in the ASW fight by making changes to the smallest "player"?

Let us consider the Navy's smallest player, the sonobuoy, or more specifically, the directional frequency analysis and recording (DIFAR) sonobuoy. According to DOSITS (2015), the DIFAR sonobuoy is a passive acoustic sonobuoy that uses "a hydrophone to listen for sound energy from a target"; then, the "directional hydrophone gives bearings to where the acoustic signal originated." DOSITS goes onto explain that DIFAR sonobuoys can "detect an acoustic signal with frequencies ranging from 5 to 2,400 Hz and can operate up to eight hours at depths of up to 1,000 feet." The U.S Navy has been and is still using sonobuoys. They are highly effective when used by an airborne asset; however, if a ship uses them, the chances of a submarine actually going through the field laid by the ship are slim to none and more importantly if sea state is too high then the ship loses the ability to utilize the sonobuoy at all. Overall, this technology needs to be updated and improved

Now imagine a sonobuoy powered by sonar panels, increasing its on-station time, with the capability to have communication signal with a range greater than line of sight (LOS). Imagine a sonobuoy that has an onboard processor that can utilize pre-programmed historic sound speed profiles (SSP), and deploy a passive array with an advanced acoustic sensor. Taking into account these capabilities and with the help of an UAV called the "Aqua-Quad," one now has an asset that can stay on station longer than eight hours, can communicate with ships, air assets, and even friendly submarines, and lastly can deploy a passive array at depths that increase the probability of detection (Pd) significantly.

Currently under development, the Aqua-Quad is an energy-independent, ultra-long endurance, hybrid-mobility unmanned system that measures just over one meter in diameter. The prototype is a quad-rotor air vehicle with a 20-cell photovoltaic array distributed around the four propeller disks. These four water-tolerant propeller disks are 356 mm in diameter and made of carbon fiber. The 20-cell array uses monocrystalline Si SunPower E60 cells with roughly 24% efficiency. These cells are the sole source of energy for all operations of the Aqua-Quad and they must power avionics and sensors all the time, as well as energy for flight a few times per day. Outside of the quad-rotors and solar panels there is a watertight enclosure that will hold all of the electronics that includes both the processor and power board. This enclosure must provide the necessary buoyancy and stability to keep the Aqua-Quad afloat in rough seas.

The Aqua-Quad has the capability to reposition itself to either its original location, compensating for drift, or continue to track a moving target. Working cooperatively, the tracking task can be handed from one Aqua-Quad to another to further extend the tracking range, while all Aqua-Quads in the flock utilize hybrid mobility, employing an optimized combination of drifting and flying segments to relocate. Having multiple Aqua-Quads will help with beam forming, which will essentially give better ranges as well as add a direction capability that DIFAR sonobuoys cannot do. Communication with other assets is relatively simple as well. The Aqua-Quad, when needed, can lift to a sufficient altitude and pass on information about the contact such as course, speed, and even classification by RF/HF/UHF/Iridium communication.

A. EXPERIMENTATION

Since the Aqua-Quad is still in development, experiments were performed with just the outer shell of the prototype, with added weight to bring it up to the expected full system weight, for the purposes of evaluating stability and shell integrity in various sea-states. Setup included the Aqua-Quad shell with motors and propellers mounted along with an Acousonde sensor fastened to a 10m line under the Aqua-Quad. An evaluation of this capability was a primary goal of the experiments described herein. For experimentation a live Acousonde was used as the acoustic sensor, simply attached to a

marine buoy to collect acoustic data for the experiment. The prototype-flying model with lower enclosure removed is shown in Figure 1.

Figure 1. Aqua-Quad Prototype

Source: Jones, K., 2015: Development and Testing of the Aqua-Quad. CRUSER Newsletter, Dept. of Mechanical and Aerospace Engineering, Naval Postgraduate School, 4pp.

The Acousonde was placed at depth to record acoustic data from a sound source in order to verify the usage of the Aqua-Quad as a sonobuoy asset. A Castaway CTD was used to measure the SSP at two different locations in the Monterey Bay to determine the mixed layer depth.

Additionally, the experiment provided some initial data on the survivability of Aqua-Quad in various ocean sea states. Results from the experiment are summarized in the following sections.

1. Survivability

During initial experiment, the shell of the Aqua-Quad was used with all four motors and propellers installed; however, there were no electronics on board. Equivalent weight was added to simulate the weight of the missing electronics and batteries. The Aqua-Quad was deployed in the Monterey Bay at two locations to test survivability and buoyancy limitations, first in calm water, and later in rougher conditions. There was a

small craft advisory on the day of the experiment with swells expected at 11–14 feet at 13 seconds, making it a perfect day to verify that the prototype would stay afloat.

At the location of deployment 1, shown in Figure 2, the sea state was calm with swells from 2–4 feet. This allowed for an evaluation of basic survivability and to make sure the shell would not take on water and sink. To do this, the Aqua-Quad was deployed over the side of the rigid-hull inflatable boat (RHIB), as shown in Figure 3, and tethered to a marine buoy, as shown in Figure 4, to ensure recovery of the prototype if it proved to be unseaworthy. The Aqua-Quad successfully stayed afloat and rode the mild swells very well with minimal water washing over the solar panels, which will be important for maintaining good solar performance while the Aqua-Quad stays on station for extended periods. Once the test was deemed successful, the marine buoy was untethered from the RHIB and allowed to drift freely with the waves, but with the Aqua-Quad still tethered to the buoy for safety. The Aqua-Quad drifted north to northwest for approximately 115 yards in 30 minutes after the buoy was untethered from the RHIB. After approximately 45 minutes, the buoy and the Aqua-Quad were retrieved. The interior of the Aqua-Quad shell was completely dry.

Figure 2. Location of Deployment 1, just outside the Monterey Harbor

Source: Google Earth. Accessed and downloaded 24 November 2015. [Available online at https://www.google.com/earth/explore/products/desktop.html.]

Figure 3. Initial Deployment of Aqua-Quad

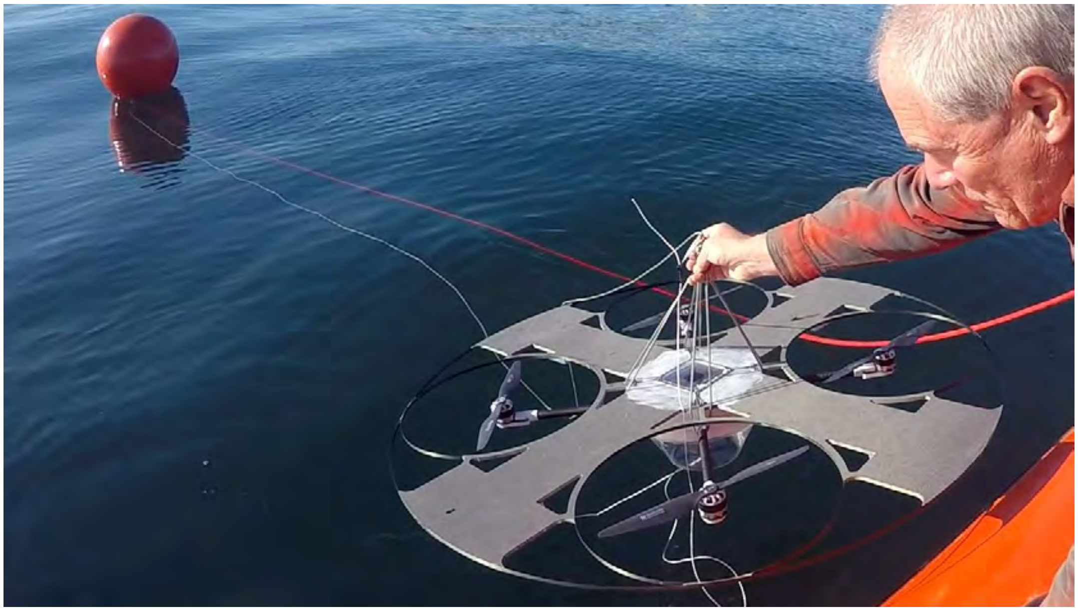
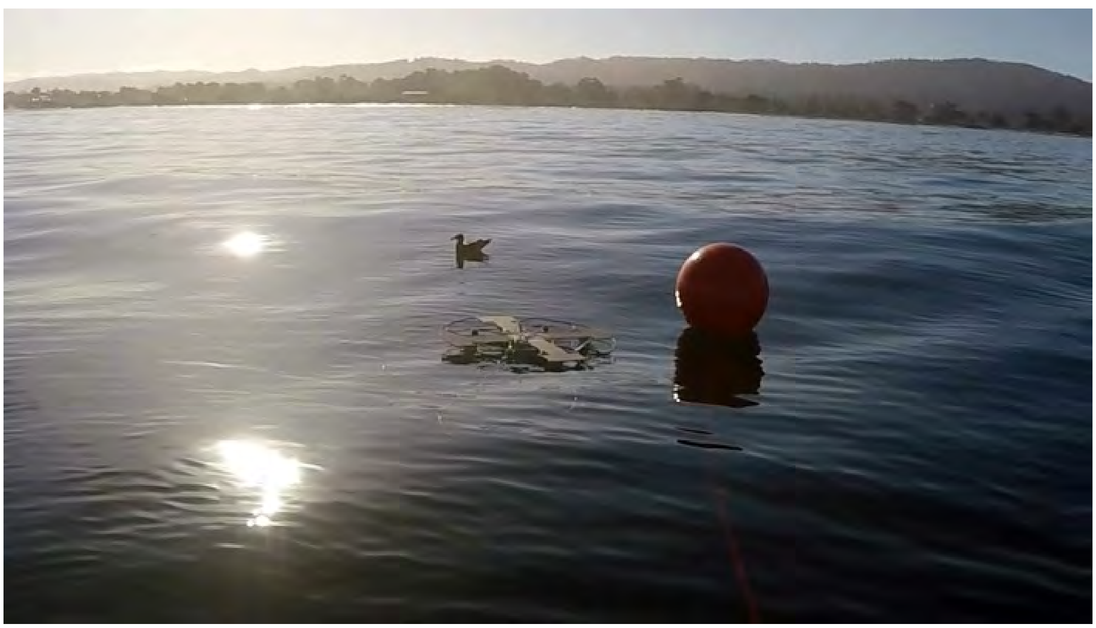
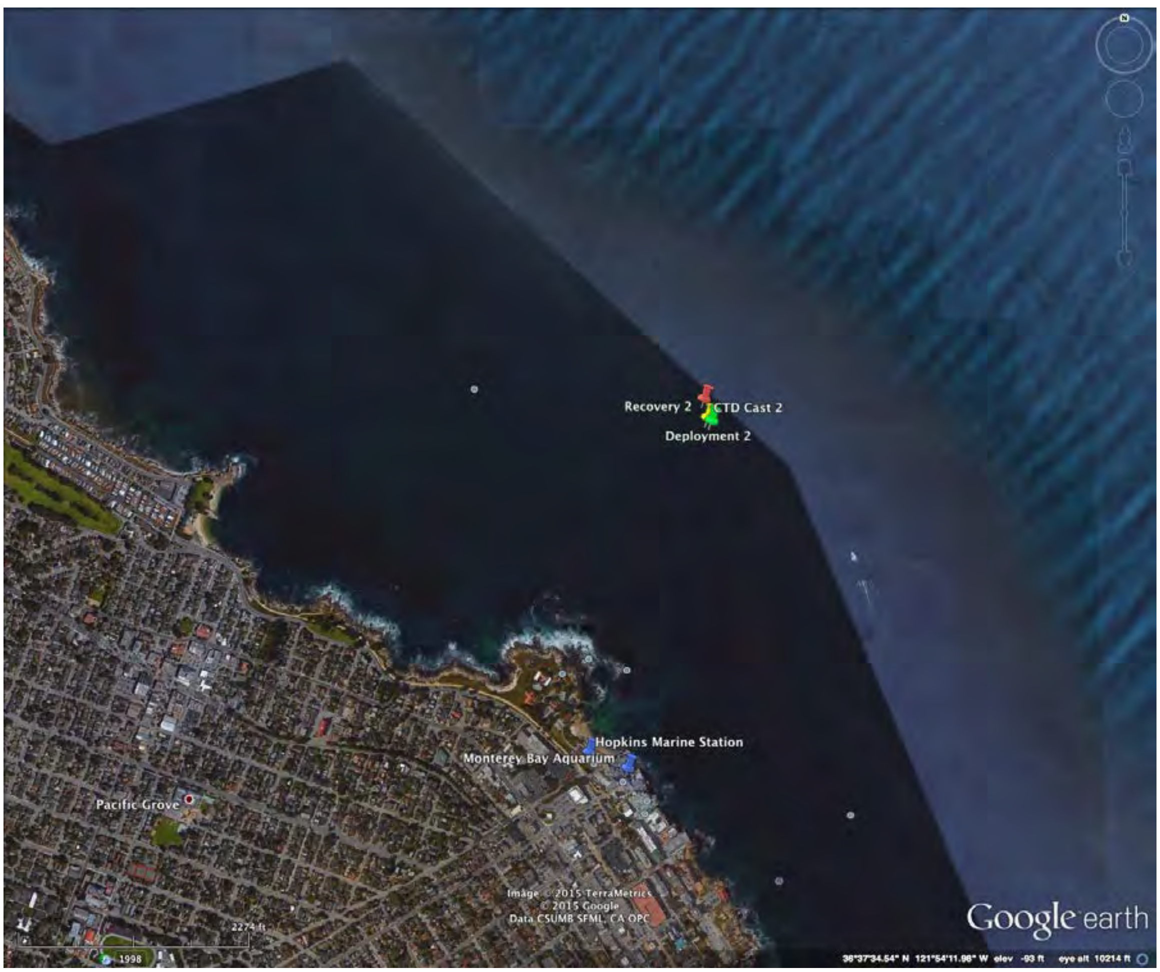


Figure 4. Deployment 1 Setup



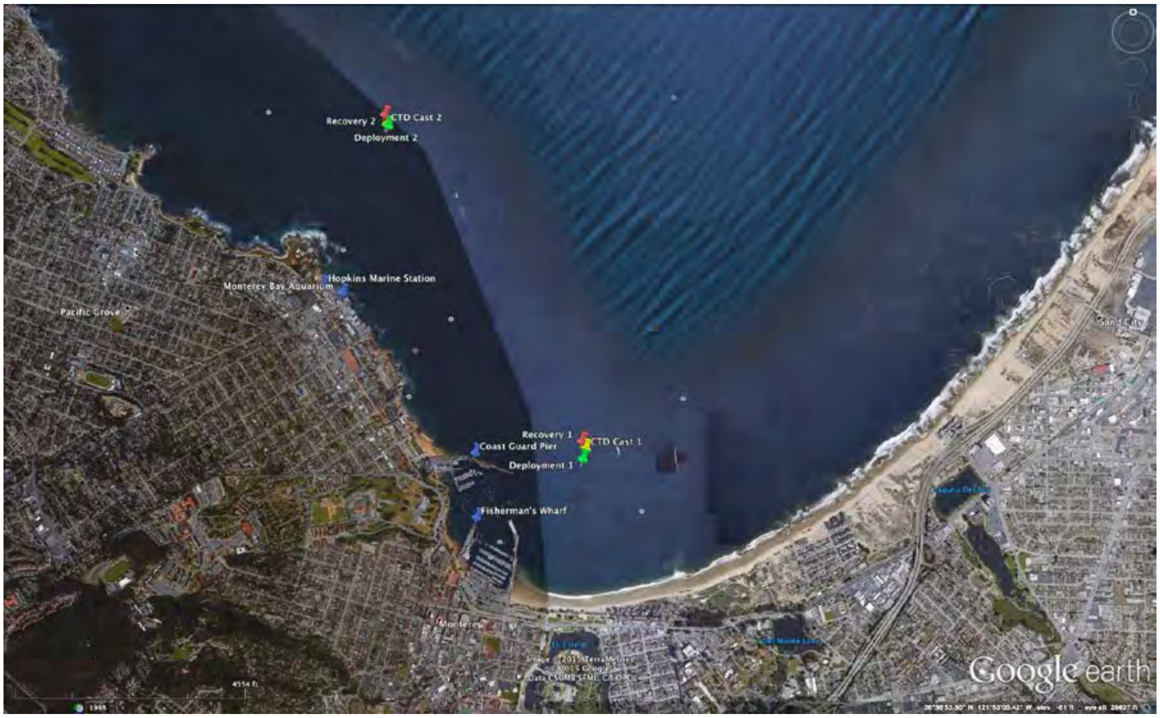
At the location of deployment 2, pictured in Figure 5, the sea state worsened quite a bit with swells of 6–10 feet; however, the Aqua-Quad had no issues and the solar panels still remained relatively dry. It was noted that the buoy and the Aqua-Quad, which were tethered to each other, drifted somewhat differently, and as the tether became taught, the floatation of the Aqua-Quad appeared to be adversely affected by the line tension. Although the second experiment was shorter, the Aqua-Quad still drifted approximately 78 yards during a time period of about 20 minutes. The distance between each deployment site was approximately 2,700 yards, as shown in Figure 6. The Aqua-Quad afloat in a rising sea state is shown in Figure 7.

Figure 5. Location of Deployment 2, near the Hopkins Marine Laboratory



Source: Google Earth. Accessed and downloaded 24 November 2015. [Available online at https://www.google.com/earth/explore/products/desktop.html.]

Figure 6. Full Experiment Deployment/Recovery Location



Source: Google Earth. Accessed and downloaded 24 November 2015. [Available online at https://www.google.com/earth/explore/products/desktop.html.]

Figure 7. Aqua-Quad in Rising Sea State

2. Sound Speed Profile

The sound speed profile (SSP) was measured using a CastAway CTD, shown in Figure 8. The CTD was attached to a line that could be reeled in and out of the RHIB allowing the sensor to traverse much of the water column. A weight was attached to the end of the line to counteract the buoyancy of the CTD and pull it down through the water.

Figure 8. CastAway CTD Utilized for Instantaneous Profiles of Temperature, Salinity, and Sound Speed

Source: SonTekCastaway-CTD, 2015. Accessed 24 November 2015. [Available online at http://www.sontek.com/productsdetail.php?CastAway-CTD-11.]

The product description on the CastAway CTD's website claims: "the system that incorporates modern technical features that allow it to achieve a 5 Hz response time (sample rate), fine spatial resolution and high accuracy. Plots of temperature, salinity, and pressure (TSP) versus depth can be viewed immediately on the integrated color LCD screen along with the associated SSP. All data can be easily downloaded via Bluetooth to a computer for detailed analysis. The CTD can be used in water depths of up to 100m (SonTek 2015)." SonTek (2015) also states accuracy of all measurements is as follows:

- Salinity Accuracy: 0.1 PSU
- Temperature Accuracy: 0.05 °C
- Pressure Accuracy: 0.25% of FS
- Sound Speed Accuracy: ±0.15 m/s

At both deployment locations the SSPs, shown in Figures 10 and 12, are very similar with a 10-meter surface layer followed by a thermocline to 15 meters. One will also notice that at the deployment location 1 the max depth is 20 meters and at the deployment location 2 the max depth is 50 meters. The difference in depth did not affect the SSP, due to the similarity of the TSP, as shown in Figures 9 and 11.

Figure 9. TSP Deployment Location 1

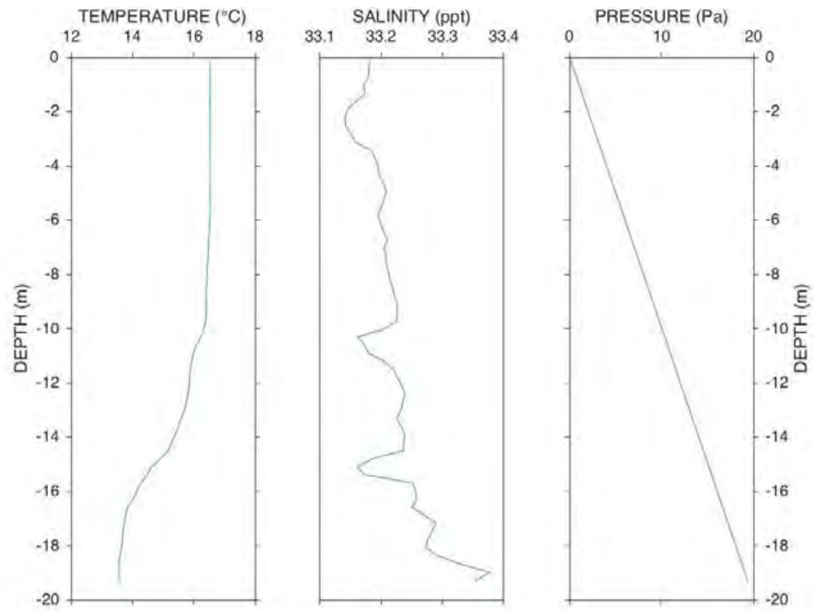


Figure 10. SSP Deployment Location 1

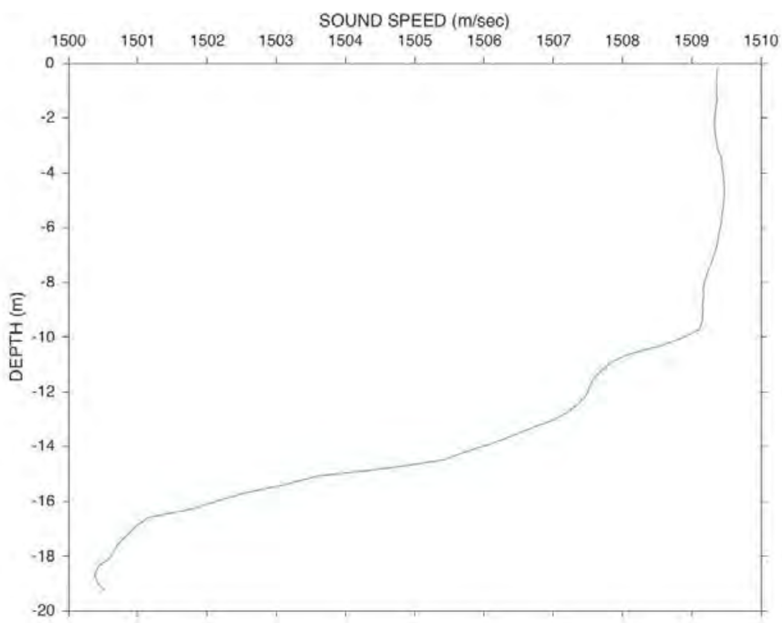


Figure 11. TSP Deployment Location 2

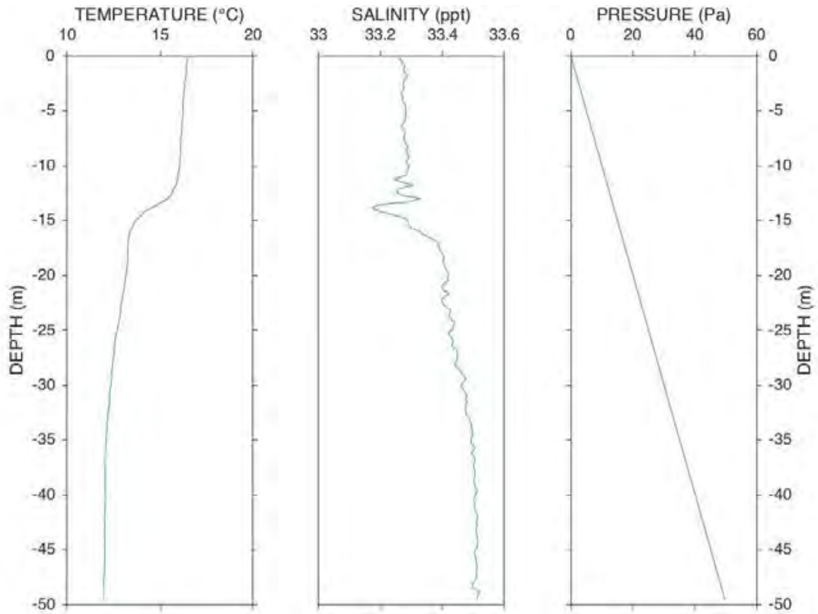
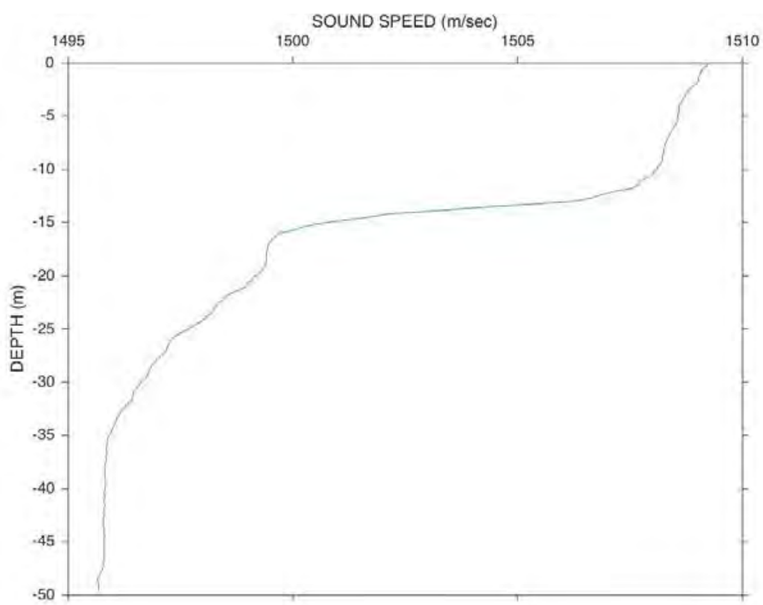


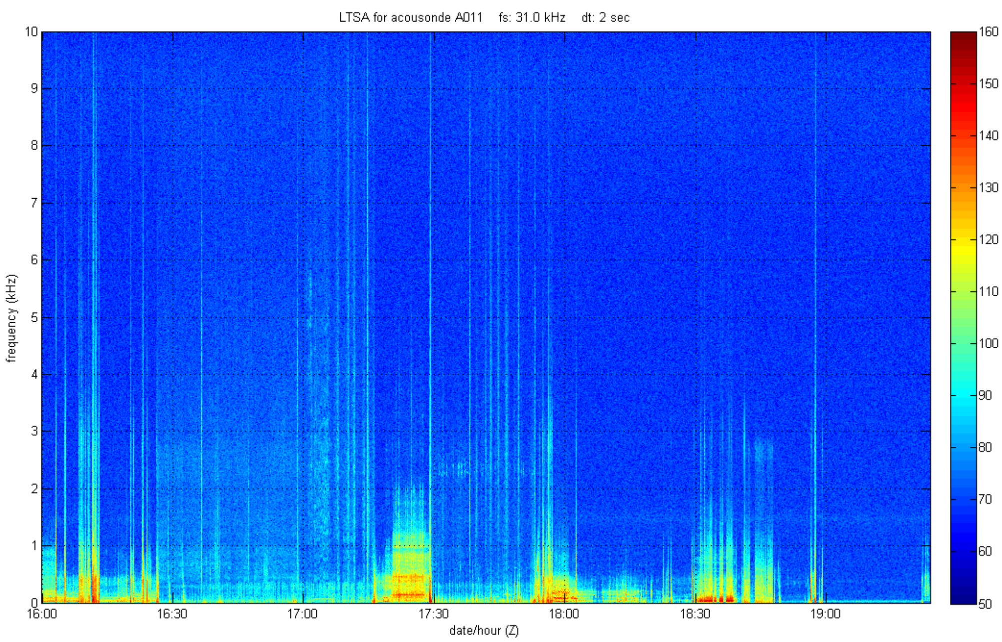
Figure 12. SSP Deployment Location 2



3. Acoustic Data

The Acousonde collected acoustic data over the entirety of the experiment and even collected data outside of the ocean environment. The summary of long-term spectral averages (LTSA) of the acoustic data over the two and a half hour experimental period is shown in Figure 13.

Figure 13. Summary LTSA



The legend colors represent the frequency in kilohertz in all of the figures. Each plot shows the amount of acoustical frequency that was recorded by the Acousonde from the sound source. The RHIB was used as the sound source for the collection of data. After successful deployment of the Aqua-Quad and verification that it could handle the sea state, the RHIB made several high speed passes with a closest point of approach (CPA) no closer than 100 yards. The high-speed runs are apparent in Figures 14 and 15 between the times of 1630Z and 1715Z and also between 1730Z to 1800Z. The lower frequency ranges in those time equates to the sounds of the RHIB as it conducted passes near the Aqua-Quad and the tethered Acousonde. As seen in the cropped time frames,

the Acousonde was very successful at picking up the low frequency sounds of the RHIB. In both Figures 14 and 15 between the stated times, the RHIB made various high-speed runs. The narrow cyan spikes correspond to the RHIB bouncing on the water. On both ends of those runs, the higher frequency corresponds to the recovery and deployment of the equipment. Overall, acoustic data collected by Acousonde was very efficient and simply proves that the Aqua-Quad is that much closer to becoming the new and improved sonobuoy for the Navy. In the future, utilizing digital input/output sensors will make the transfer of information that much easier for the Aqua-Quad’s processor.

Figure 14. Zoomed-in LTSA, Time 1620–1725Z

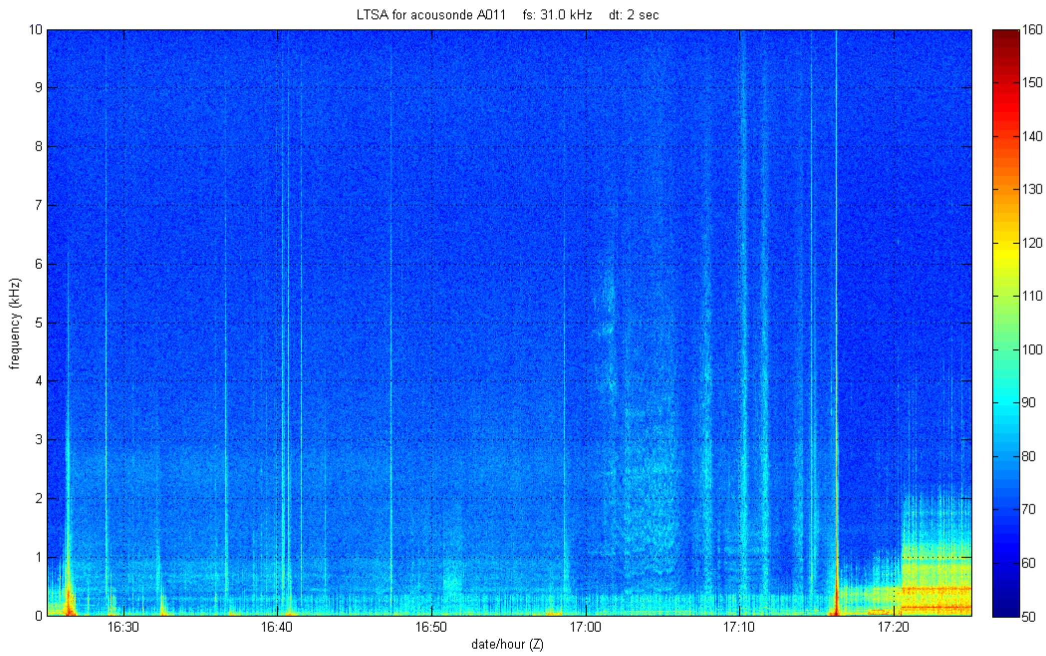
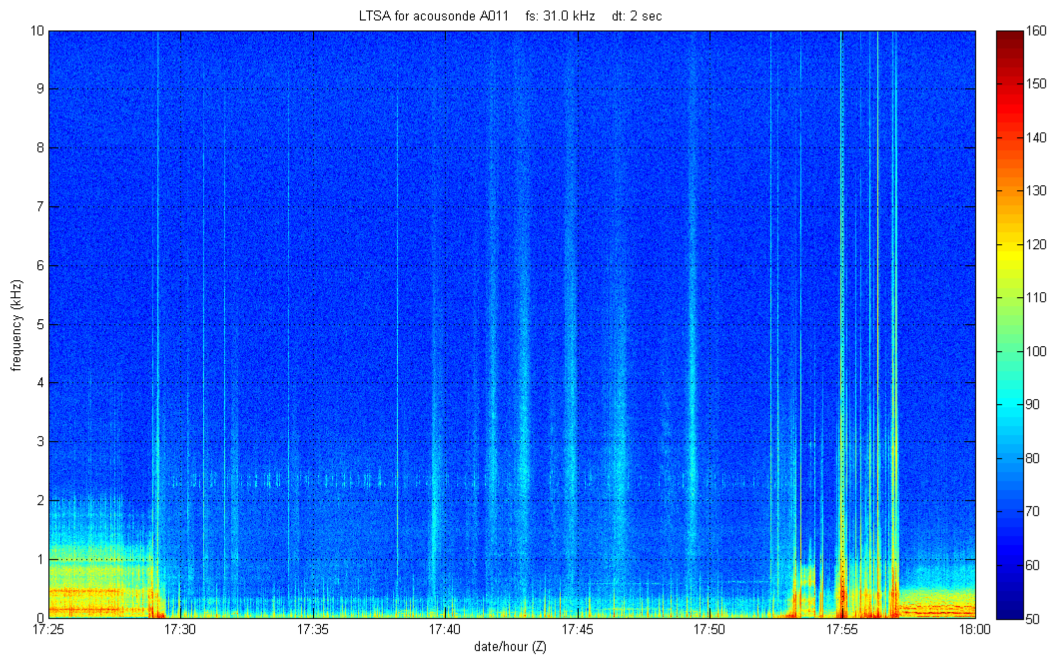


Figure 15. Zoomed-in LTSA, Time 1730–1800Z



4. Summary

The experiment conducted on 3 November 2015 was a chance to verify survivability of the Aqua-Quad in both calm and semi-rough sea states. It also provided the Aqua-Quad a chance to simulate a deployment with an actual sensor deployed beneath the AUV. Overall the experiment was a complete success as the Aqua-Quad behaved above expectations and showed it is ready, after a little more development, for the next step of becoming an asset for the U.S. Navy.

5. Post-Experiment/Lessons Learned

After the experiment concluded and a few days passed, the Aqua-Quad's four motors felt a little "crusty"; however, after spinning them for a few seconds, everything worked normally with no issues. This being said, as the operating system is determined and built, programming the propellers to startup and idle for a few seconds every couple of hours while on station might help prevent fouling that would prevent the Aqua-Quad from flying. Also while inspecting the Aqua-Quad after the rough-water operational test, it was noticed that there was a small amount of water inside of the enclosure. It was later

determined that this was due to insufficient water sealing where the motor wires enter the enclosure. Lastly, during the experiments, the safety tether to the buoy created unrealistic forces on the Aqua-Quad, frequently tipping it such that the solar arrays were partially submerged some of the time. It is recommended that in future tests an alternative tether arrangement or no tether at all be utilized to avoid this.

B. QUANTITATIVE/QUALITATIVE ANALYSIS: AQUA-QUAD VERSUS DIFAR SONOBUOY

There are many programs in the Navy, and with each of these programs the leading "cons" will be cost to produce, cost to repair, cost to deploy, and cost of maintenance. Each program that is introduced will be compared to its counterpart to make sure that the newer program or asset is the right way to go or the right decision to make. This is normally done by taking historical data of the older program and comparing to the newer data of the up and coming program. Once the comparison is done, then the decision to move forward with the new program or to keep the old program is made. This comparison will take time; however, when it comes to the Aqua-Quad, the end product will yield a product that increases the ability for the Navy to continuously track an enemy COI.

A comparison of the two ASW assets is made in Tables 1 and 2.

Table 1. DIFAR Sonobuoy Pros and Cons

DIFAR Sonobuoy	
Pros	**Cons**
Years of Use	Communication (LOS only)
	Shelf-Life
	On Station Time (8 hours)
	Out-dated Technology

Table 2. Aqua-Quad Pros and Cons

Aqua-Quad	
Pros	**Cons**
Communication	Cost (at first)
On Station Time (Claiming three months)	New Technology (this will eventually become a pro)
Tracking Capability	
Ability to Transmit to other assets	
Continuous Tracking	
Ability to Autonomously determine SSP	
Allows Ship assets to be apart of ASW fight	
Ability to reposition	

The UAV/Aqua-Quad in initial comparisons has very few cons, suggesting that it merits continued research and development. When a cost comparison is done, the DIFAR sonobuoy is the cheaper option. However, while system cost for the Aqua-Quad is higher, the expected capability and endurance win by a large margin. One way to view this comparison is by a cost per hour on station. For a sonobuoy you get eight hours on station time, with no mobility, other than drift, for \$500–\$2500. As for the Aqua-Quad, the initial baseline costs of under \$10,000 gets the Navy months of on station time combined with the ability to follow the COI for extended periods. Most of the cost for the Aqua-Quad is coming from solar arrays and batteries; however, the solar arrays are one of the major reasons that the Aqua-Quad will be a better asset than the DIFAR sonobuoy. A more in-depth look of DIFAR sonobuoys shows an asset that cannot be repaired if it's damaged. Furthermore, there is also no maintenance done on them except to verify shelf life and once this expires the sonobuoy becomes Code Hotel, ammo term for expired, and is shipped to a facility where it is either de-militarized or the battery is replaced and then it is reintroduced into service depending on buoy type. A second con is simply that the Aqua-Quad is not necessarily new technology but it is a new asset. When introducing a new asset/system to the fleet there comes with the introduction, the time it

takes to learn how to use the new asset/system and integrate it into the already installed systems on the ship and aircraft. The importance of time is not a deal breaker as the DIFAR sonobuoy is a trusted asset that has been used for years that can still be used until the Aqua-Quad comes online as a fully functional UAV sonobuoy.

As stated earlier, there are very few cons and those cons are shadowed by the many pros that make the Aqua-Quad the new and improved version of an asset that will be utilized to detect, classify, and if needed support an engagement on an enemy COI. Three months of claimed on station time with the potential for up to 200 days for the Aqua-Quad when compared to the DIFAR sonobuoys eight hours is the number one pro. This exponential increase of on-station time will allow for continuous tracking and passing of information on a COI. The passing of this information leads to another pro. The DIFAR sonobuoy has a LOS limitation, ten nautical miles max depending on sea state, of passing the information on the contact. Although this is only a real downfall for surface assets, it takes away an asset that is left out of the ASW fight. The Aqua-Quad has many possible options when it comes to communication to pass contact information from Aqua-Quad to Aqua-Quad and from Aqua-Quad to surface/air asset. If Iridium communication is used, then we may not have to fly for communication, but bandwidth will be small. Utilizing UHF/VHF vice Iridium, the Aqua-Quad would then have to lift off the ocean surface for communication but we gain the advantage of high bandwidth. However with UHF/VHF there is lower range but to counter the lower range , a ship could use a high gain tracking antenna to point a narrow beam at the flying Aqua-Quad, opening the range up to 20 miles in any sea state. This will play a key part in integrating surface assets back into the ASW war fight. It is stated later in the thesis but this UAV could have a set up that could allow for the METOC world to utilize the Aqua-Quad as a mobile constant SSP/weather system information gatherer. Rather than having surface assets in the AOR drop XBTs, the Navy could tactically place Aqua-Quads throughout the AOR to collect information. This brings the next pro of the Aqua-Quad to reposition to its starting position at the end of a tracking cycle. Repositioning using the ability to lift off the ocean surface and maneuver back to its starting GPS position is another pro that

allows for constant acoustic tracking of a COI or for constant SSP/weather system tracking.

In summary, the Aqua-Quad in the ASW environment has plenty of pros that make it worth the initial costs to produce and definitely worth the research and testing to be a positive asset for the Navy. It not only can stay on station for an exponential amount of time more than a DIFAR sonobuoy but the ability to communicate with other assets outside a range of LOS allows for the reintegration of surface forces back into the ASW fight. Repositioning to original start location allows for constant acoustic sensing in an AOR. This plays a major role when it comes to finding and tracking enemy COIs. Lastly, the Aqua-Quads depth of usage spans over many areas of the Navy from ASW/USW to Cyber Warfare to METOC, thus beating the traditional DIFAR sonobuoy "hands down."

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III. CONCLUSIONS AND FURTHER WORK

In this thesis, the baseline of one road the Aqua-Quad can travel was introduced. There are many mission-sets that have been proposed and with further work and research those mission-sets can be evaluated but in this thesis we evaluate the application to USW. Whether it is tracking an enemy submarine or semi-submersible, the Aqua-Quad shows the promise to one day be a vital asset once further research and development as well as at-sea testing are performed to quantify its capabilities and limitations. We have just broken the surface on the possibilities that the Aqua-Quad can be used for in the war fight.

A. CONCLUSIONS

This thesis presents a first look at an asset that may be heavily utilized once the appropriate amount of research is conducted and the final product is produced. It will be a team effort through all realms of engineering as each part of the Aqua-Quad will be built and researched by multiple avenues of engineering. There is a prototype to work from and initial experiments have been conducted on both survivability in an advanced sea state and a test of the solar recharge sub-system, both of which were extremely successful and provided multiple lessons learned and even suggestions on ways to move forward to more in depth testing. Most of these lessons and suggestions point in the direction of maximization of the Aqua-Quad. Maximization meaning producing a final product that will do exactly what it is advertised to do with no issues and at the highest level of completion. More specifically, moving in the right direction to allow for an on station for up to 200 days, being able to communicate autonomously not only with other Aqua-Quads but with other assets as well, and lastly continuously tracking a COI or maintaining tracking coverage in an AOR.

B. FURTHER WORK

As stated in the conclusion, this thesis and research has multiple applications throughout every aspect of engineering. With continued research from Naval Postgraduate School and support from the Navy itself, this UAV has the potential to be a

game changer in the USW fight that is becoming more and more of a critical warfare area. That being said, the Aqua-Quad, although is only passive in this thesis could possibly be used as an active way of executing and engaging an enemy contact of interest. Adding an active sonar to the Aqua-Quad makes it that much more of an asset and even possibly a decoy to make the enemy contact thing it is being prosecuted by another ship or submarine when in reality it is just the Aqua-Quad with a "dipped" sonar pinging to make the COI either actively engage or maneuver causing it to be tracked by an asset that can engage and destroy the COI.

For the vehicle itself, there is plenty of further work to be done. There is a prototype that is headed in the right direction but there is still a vast amount of evaluating that needs to occur before the potential of the Aqua-Quad can fully be used for any means. The potential thesis topics below are just a starting point for working in specific areas that once researched will be combined to maximize the Aqua-Quad to become the new and improved sonobuoy that many people know it can be. Outside of the thesis topics, communication capability is an area that needs to be determined so that each Aqua-Quad can not only talk to each other but also can talk to other assets and pass on information. Next, is the task of figuring out if the Aqua-Quad has the ability to self-right after possibly being flipped over in the ocean environment.

There are many potential thesis topics starting with aerodynamic performance and flight controls of the vehicle, circuit design and complete system optimization. There are even operational application theses that can span over various warfare/Naval areas such as USW, Cyber, and Meteorology and Oceanography (METOC).

1. USW

This thesis initializes the USW portion of the Aqua-Quad. An in-depth look of specific AORs that are of high interest to the United States such as the South China Sea and even SOUTHCOM AOR for the use of finding fully and semi-submersible submarines to verify that the potential for the use of Aqua-Quad is great enough to produce the Aqua-Quad for USW purposes, especially in these areas of high interest. We are looking at deploying enough Aqua-Quads to be used as a barrier across some span

where there is expected to be enemy submarine traffic. Once any one of the Aqua-Quads on station detects a submarine, the Aqua-Quads will perform a leap-frog type maneuver and continually track and pass target information to each other to track the submarine for as long as possible. Determining the appropriate sensor to use that will plug and play with the Aqua-Quad with minimal resistance and minimal power usage is the next step in moving in the right direction and key to continually tracking an enemy COI. There are many options available for sensing, however, at the moment we are thinking a passive acoustic sensor with bearing for the initial Aqua-Quad model. This sensor combined with an array of temperature sensors along the length of the tether will help with determining the SSP while the Aqua-Quad floats on the surface. Along with finding this sensor, getting permission to use air space to verify that the current prototype setup can land and takeoff in a certain sea state would also verify that we could move forward in production of the prototype.

2. CYBER

Utilizing the Aqua-Quad for cyber missions have been proposed as well and with cyber warfare being the warfight of the future, the Aqua-Quad once again can be utilized as a game-changing asset.

3. METOC

Employment of the Aqua-Quad as a means of determining METOC information such as determining locations of weather systems and even deploying a continuous XBT type device to collect information on SSP and surface/thermocline layers to help assets in a specific area know where to deploy their sensors for USW/ASW. The Aqua-Quad can perform both water sensing and atmospheric sensing, making it a potentially very good asset for air/sea boundary layer characterization. This is critical for predicting RF propagation for radar and communication. Predicting this propagation is extremely helpful for surface assets when determining how far their radars can detect enemy weapons.

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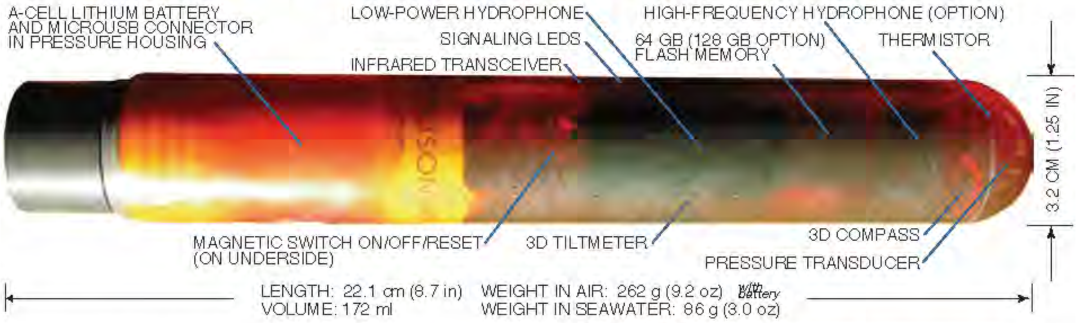
APPENDIX A. ACOUSONDE TECHNICAL SPECIFICATIONS

ACOUSONDE™



The *Acousonde*™ is a self-contained underwater acoustic recorder comprising one or, optionally, two hydrophones, sensors for attitude, orientation, depth and temperature, a digital recorder, and a field-replaceable battery. Attached to a subject with suction cups or other means, the Acousonde measures the subject's sound environment as well as potentially associated behavior.

Lori Mazzuca

Ward Testa

In addition to its primary mission as a tool for assessing the impact of noise on marine wildlife, the Acousonde can be used to study vocalization behavior of the tagged subject. The instrument may also be applied as an autonomous recorder suspended from a cable, placed on the seafloor, or housed in a robotic or remotely-operated vehicle.

Lori Mazzuca

SPECIFICATIONS, ACOUSONDE 3A UNDERWATER ACOUSTIC RECORDER

Maximum operating depth (fixed build option)	500 m (-500m suffix) / 1000 m (-1km) / 2000 m (-2km) / 3000 m (-3km)
Maximum continuous acoustic sampling rate	232 kHz
Anti-alias filter, low-power (LP) channel	8-pole elliptic, adjustable (automatic) up to 9.2 kHz maximum
Anti-alias filter, high-frequency (HF) channel	6-pole linear phase, fixed
3-dB anti-alias cutoff	9.2 kHz (LP chan max); 42 kHz (HF chan)
22-dB anti-alias cutoff	11.1 kHz (LP chan max); 100 kHz (HF chan)
3-dB high-pass cutoff	22 Hz (LP chan); 20 Hz/1 kHz/10 kHz (HF chan, fixed, customer spec)
Unamplified raw ceramic sensitivity, re 1 V/μPa	-201 dB (LP chan hydrophone) & -204 dB (HF chan hydrophone)
Saturation at 0-dB gain, re 1 μPa zero-peak	187 dB (LP chan) & 176 dB (HF chan)
Acoustic gains, selectable at deployment	0 or +20 dB
Acoustic sampling resolution	16 bits
Auxiliary sampling rate	Up to 800 Hz (3D tilt), 40 Hz (3D compass), 10 Hz (depth, temp)
Auxiliary sampling resolution	16 bits (except 10 bits for tilt)
Auxiliary sampling channels	Depth (pressure), internal temperature, 3D tilt, 3D compass
Total storage capacity (primary & spare)	64 GB, 128 GB max (*at sample rates < 26 kHz, battery limits storage*)
Maximum duration if sampling < 26 kHz	6-14 days depending on temperature and if aux sampling also active
Maximum measured data download rate	3.3 GB/hour via MicroUSB connector

December 2013

Firmware support for some specifications, performance and/or functionality may be pending; see current release notes. Data subject to change without notice.

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The Acousonde™ is made by Acoustimetrics, a brand of Greeneridge Sciences, Inc.

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APPENDIX B. CASTAWAY-CTD SPECIFICATIONS

CastAway CTD

SPECS

The CastAway®-CTD
with profiling and analysis software

The CastAway-CTD
Accurate, reliable data in the palm of your hand!

APPLICATIONS:

- Coastal Oceanography
- Hydrology
- Aquaculture/Fisheries
- Saltwater Intrusion
- Surveying/Hydrography
- Sound Velocity Profiles
- Field Sensor Verification
- Estuarine Research

The CastAway-CTD is a lightweight, easy to use instrument designed for quick and accurate conductivity, temperature, and depth profiles. Starting with a unique six-electrode conductivity cell and fast response thermistor the CastAway makes use of modern technology to provide state of the art CTD measurements.

The CastAway incorporates the most modern technology available yet is simple to use. It is designed for profiling down to 100 m and is easy to deploy.

The palm-sized CastAway-CTD can easily be deployed from small boats. Each cast is referenced with both time and location using its built-in GPS receiver. Plots of conductivity, temperature, salinity and sound speed versus depth can be viewed immediately on the CastAway's integrated color LCD screen in the field.

The rugged, non-corrosive housing, AA battery power and tool-free operation reflect the technician-friendly pedigree of the CastAway-CTD. Profile data is easily downloaded via Bluetooth to a Windows computer for detailed analysis and/or export. The CastAway software displays profiles of the casts in addition to mapping the locations of the data collection points. Data can also be exported to Hypack or Matlab and integrates with RiverSurveyor software for applying sound speed corrections.

HIGHLIGHTS:

- *5Hz response and sampling rate*
- *Accurate to 0.1 PSU, 0.05°C*
- *Internal GPS*
- *Bluetooth wireless data download*
- *No user calibration required*
- *No tools, computers or cables required*

The CastAway-CTD is fully compatible with the RiverSurveyor S5/M9

sontek.com/castaway

CastAway CTD

Specifications

To order, or for more information, contact SonTek at inquiry@sontek.com

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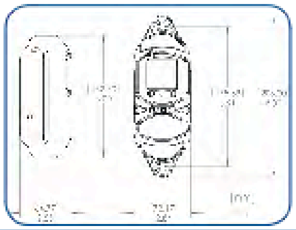
ISO 9001
ISO 14001
San Diego, California, USA

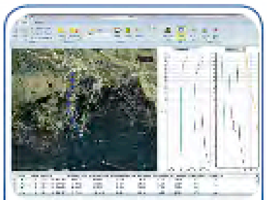
CE

Sound Principles.
Good Advice.

Memory	15 MB (750+ casts based on typical usage)
Communications	Bluetooth class II, up to 10 m range
Power	2 "AA" alkaline batteries, 40 hours continuous use
Data Output Format	- ASCII (CSV) -Hypack -Matlab
Environmental	- Depth range: 0-100 m - Use temperature: -5° to 45° C - Storage temperature: -10° to 50° C
Sampling Modes	- Casting (up/down) - Point sample (moving the unit back and forth)
Software	- Windows XP/Vista/7 - Geo-referenced - Multi-language - Data plots, filtering, import/export
Accessories	- Rugged plastic storage/shipping case - Polyurethane jacket - 15m deployment line - Bluetooth dongle - Two locking carabiners - Three magnetic stylus pens - Cleaning brush
Thermistor Response	Less than 200 ms (5 Hz)
Sampling Rate	5 Hz
Weight	In air: 1.0 lb (0.45 kg) In water: 0.06 lbs (0.03 kg)



Simple "AA" battery installation and storage area for spare stylus.



A screen capture of data from a river delta in Louisiana acquired using a CastAway-CTD. 21 casts were collected in less than 3.5 hours.

Each CastAway ships in this rugged plastic case, complete with accessories and quick start guide.

The CastAway-CTD Output Parameters

	Range	Resolution	Accuracy	Measured or Derived
Conductivity	0 to 100,000 µS/cm	1µS/cm	± 0.25% ± 5 µS/cm	Measured
Temperature	-5° - 45° C	0.01° C	± 0.05° C	Measured
Pressure	0 to 100 dBar	0.01 dBar	± 0.25% FS	Measured
Salinity	Up to 42 (PSS-78)	0.01 (PSS-78)	± 0.1 (PSS-78)	PSS-78[3]
Sound Speed	1400 - 1730 m/s	0.01 m/s	± 0.15 m/s	Chen-Millero[4]
Density[1]	990 to 1035 kg/m^3	0.004 kg/m^3	± 0.02 kg/m^3	EOS80[5]
Depth	0 to 100 m	0.01m	± 0.25% FS	EOS80[5]
Specific Conductivity[2]	0 to 250,000 µS/cm	1µS/cm	± 0.25% ±5 µS/cm	EOS80[5]
GPS			10 m	

[1]Based on temperature resolution and accuracy.
[2]Based on 100,000 µS/cm at -5° C.
[3]1978 Practical Salinity Scale.
[4]Chen-Millero, 1977. Speed-of-sound in sea water at high pressures.
[5]International Equation of State for sea water (EOS-80).

sontek.com/castaway

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